Effectiveness of Peripheral Level of Detail Degradation When Used With Head-Mounted Displays

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ABSTRACT

Two user studies were performed to evaluate the effectiveness of level of detail (LOD) degradation in the periphery of head-mounted displays. In the first study, spatial detail was degraded by reducing resolution. In the second study, detail was degraded in the color domain by using grayscale in the periphery. In each study, ten subjects were given a complex search task that required users to indicate whether or not a target object was present among distractors. Subjects used several different displays varying in the amount of detail presented. Frame rate, object location, subject input method, and order of display use were all controlled. Primary dependent measures were search time on correctly performed trials, and the percentage of all trials correctly performed. Results indicated that peripheral LOD degradation can be used to reduce visual complexity by almost half without hurting performance. Users were more sensitive to decreases in LOD than increases in degraded display area.

INTRODUCTION

As virtual environments (VE) researchers attempt to broaden the range of applications for VE technology, they are attempting to display ever larger and more complex models. Many of these models, however, cannot be displayed with acceptable frame rates in current systems. Several researchers have identified this “frame” or ”update rate” problem as one of the most pressing facing the VE community [9, 15]. Foremost among the proposed solutions to this problem is the idea of varying “level of detail” (LOD). As used by most VE researchers, this phrase refers to model and rendering complexity, which can be varied to ensure that VEs are rendered at some minimal frame rate.

Although the LOD approach holds promise, careful consideration should be given not only to the computational cost of varying detail, but also to the perceptual cost. If two rendering techniques make similar demands on the graphics engine, but the use of one of the techniques makes only a minimal contribution to perceptual fidelity or presence [13, 18], then that technique should be the first to go in the effort to maintain frame rate. Any other decision would clearly be wasteful. Thus the goal of any LOD technique should be twofold: to maximize computational gain while minimizing perceptual impact.

There are many techniques that might be used to generate images of varying complexity, including using geometric models of varying degrees of accuracy [5, 11, 14, 16], lighting and shading models of differing levels of realism, and textures and graphics windows of differing resolution [8]. Many researchers have compared the relative importance of different graphics rendering techniques in traditional display environments [1, 2, 4]. In general, these studies showed significant effects on performance when image complexity is varied. However, in most cases a point of diminishing returns was reached, beyond which additional image complexity and computation produced insignificant improvement in user performance. This suggests that varying LOD by using different rendering techniques may be a promising approach to solving the frame rate problem. However, we are not aware of any studies that address the perceptual cost of LOD generation by using models of varying accuracy.

Given that different LODs can be generated, they must still be managed and used at appropriate moments. Two LOD management approaches are already in widespread use. As the size of an object decreases, so does the eye’s ability to resolve its detail. Flight simulators and VE systems [6, 8] exploit this fact by using lower LODs when the visual angle of a portion of the model decreases. This technique has a proven track record in the flight simulator industry. The eye’s ability to resolve detail also decreases with retinal eccentricity [3]. This suggests the possibility of a computationally and perceptually efficient divided display containing a central, high detail inset, corresponding to the perceptual characteristics of the foveal area of the retina; as well as a surrounding, simpler periphery, corresponding to the perceptual characteristics of the peripheral area of the retina. Funkhauser & Sequin [6] and Maciel & Shirley [8] have implemented systems that degrade peripheral detail to improve frame rate. However, we are not aware of any studies evaluating the impact of managing LOD by degrading peripheral detail.

This paper describes two user studies evaluating the effectiveness of LOD management through peripheral detail degradation in head-mounted displays (HMDs). Because the focus of this study is LOD management, and not LOD generation, we chose to generate LODs simply by varying display resolution in the first study, and color content in the second. Moreover, because currently available eye tracking technology is unwieldy and expensive, we worked under the assumption that head-tracking alone would allow effective peripheral degradation in an HMD.

Our working assumption in this study was that peripheral detail degradation would result in minimal perceptual loss and significant computational gain. The computational portion of this assertion has been partially examined in [6, 8]. We attempted to verify only the perceptual portion of this assertion by measuring subject performance time and accuracy while peripheral detail was degraded over various visual extents and with various LODs.

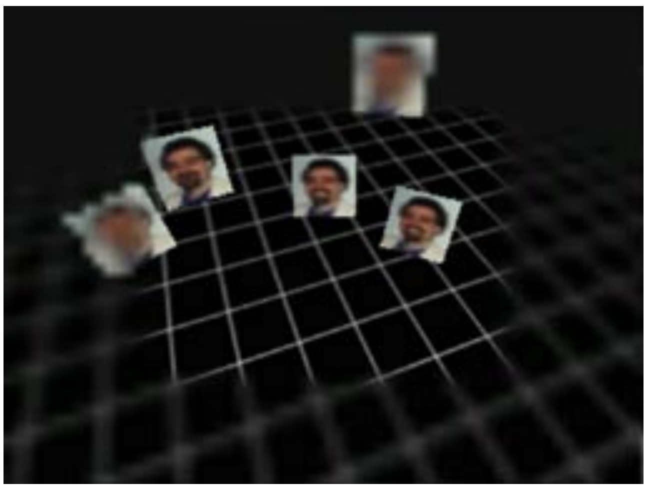

Figure 1: Experimental environment as seen with 75% degraded - coarse resolution display, grouped target present condition.

EXPERIMENT 1

In our first experiment, we varied LOD by controlling display resolution in the periphery. We used two different peripheral resolutions, and three different peripheral visual extents (see Figure 1). We compared these six displays to two evenly degraded displays using the two peripheral resolutions, as well as one undegraded display using high detail resolution. As a worst case, we chose to ask subjects to perform a search task, forcing them to make heavy use of peripheral display areas. Because visual acuity and sensitivity decrease with eccentricity, we expected that loss of detail would have less impact on subject performance time and accuracy when only peripheral detail was degraded than when detail was degraded across the entire display.

We anticipated that use of the undegraded display would result in the lowest subject performance times and highest accuracies. Finally, we predicted significant differences among the peripherally degraded displays, indicating that speed and accuracy declined as LOD decreased and the size of the periphery increased.

A preliminary study [17] indicated that the utility of peripheral LOD management would be greatly affected by the nature of the user's task. As task difficulty increases, subjects should require greater amounts of visual detail. To test this hypothesis, we varied the difficulty of the search task by varying the number and grouping of objects.

Experimental Methodology

The subjects in the experiment were 10 graduate students. All of the subjects had 20/40 vision or better.

The study utilized a six factor, mixed design. The primary independent variables were all within-subjects variables. These primary independent variables were display (varying in degraded display area and resolution, see Table 1), number of objects (1, 3, or 5), grouping (objects in the same or different quadrants), and location (location of the target object in different quadrants). In addition to these primary independent variables (used in the data analyses) the study also had three control variables. These variables were trial condition (target object was either present or absent), number of trials (there were two trials of each of the conditions), and button assignment (either the thumb or the index finger was used to signal target present). The first two of these control variables were within-subjects, button assignment was a between-subjects variable. In addition to these conditions, we also had subjects run in an evenly degraded - coarse resolution display as a check on baseline performance. The performance in this condition will be analyzed separately.

Subjects wore a Virtual Research Flight Helmet [10] to immerse themselves in the experimental environment. The Flight Helmet mounts two color LCD displays on the user's head, each with vertical field of view of 58.4 degrees, and a horizontal FOV of 75.3 degrees. Each LCD contains an array of 208 x 139 color triads, with a resolution of 38.15 arcmin at the center of the field of view. We used the Flight Helmet in a monoscopic mode by sending the same image to each of the video inputs, and mounting plastic fresnel lenses on the HMD optics to remove interocular disparity.

The motion of a subject's head in the Flight Helmet was tracked with the Polhemous Isotrak II 3D tracking hardware. The monoscopic images sent to the Flight Helmet were generated by a Silicon Graphics Onyx Reality Engine II, using the gl graphics library and the SVE virtual environments library [7]. Silicon Graphics' scan converting hardware and software were used to convert these images into an NTSC signal. Subjects used a plastic mouse shaped like a pistol grip to respond to the experimental environment. The mouse had two buttons for the thumb mounted on top, and one button for the index finger mounted on the front. The mouse was not tracked. When using the experimental environment, subjects stood inside a 4x4 platform raised six inches and surrounded by a three foot railing.

The virtual experimental environment consisted of a floor, indicated by a grid of white lines on black. The background above the floor was also black. A home object indicated starting position for search, and was textured with a bullseye design (see Figure 2). Users had no analogue of themselves in the virtual environment.

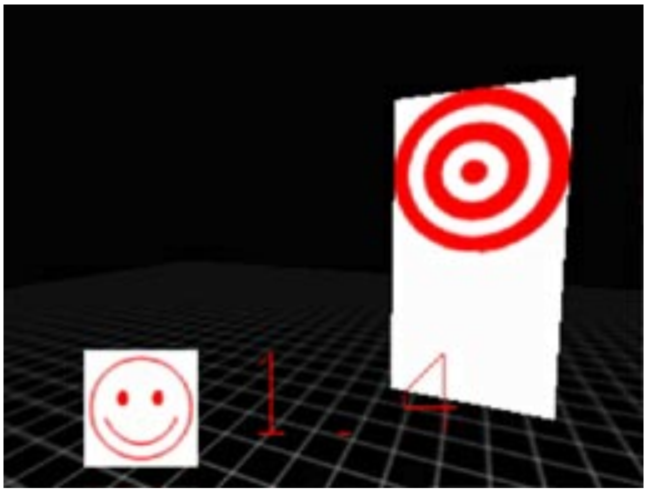

Figure 2: Experimental environment as seen with undegraded display. In view is the home object and task feedback.

During each trial, subjects would search through several randomly located, identically sized objects for a target object. Most objects were textured with identical images of a smiling human face. The single target object was textured with the same face, with the mouth closed (see again figure 1). Objects always appeared at the same virtual distance, and subtended a horizontal visual angle of approximately 12 degrees.

LOD was varied by changing resolution. When the same LOD was used across the display, a single image was generated with the required number of pixels, and then textured onto a 2D polygon with the screen size required by our scan converter. When peripheral degradation was used, two images were generated with the needed numbers of pixels, and then textured onto two polygons: one for the low LOD periphery, and one for the high LOD inset. The two polygons were overlapped slightly and blended with alpha transparency to make the boundary of the high detail inset harder to detect. Texturing was accomplished in real time with the fbsubtexload command and FAST_DEFINE [12]. Since eye tracking was not used, insets were always located in the center of the displayed image. Insets were rectangular, with the same aspect ratio as the display.

Each experimental trial consisted of a single search task. After focusing on the home object, subjects pressed a button to begin the task. After a random (between .1 and .8 seconds) delay, the home object disappeared, and objects appeared to the right of the subject's initial view. Subjects attempted to locate the target object and pressed one of two buttons to indicate if it was present. The objects then disappeared, and the home object reappeared, with on screen feedback indicating correctness and time of response (see Figure 2). When the subjects had again focused on the home object and pressed the appropriate button, a new search task began. In trials with a target object, subjects were not credited with a correct trial unless they had brought the target object into their view. In trials without a target object, subjects were not credited with a correct trial unless they had brought every object into their view. This forced an exhaustive search.

Subjects performed the search task with each of the nine display types mentioned above (see again Table 1). Although the size of the presented image was the same on all displays, resolution was varied at three levels, effectively varying pixel size. At the fine level of display resolution, the image scanned into the HMD was 25% of NTSC: 320 x 240 pixels. Medium resolution was 9% of NTSC: 192 x 144. Coarse resolution was only 1% of NTSC: 64 x 48. The high detail inset was always presented at the fine level of resolution.

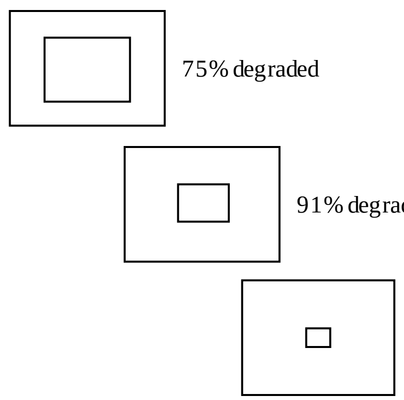

Figure 3: The three peripherally degraded levels of the display area variable. Center box contains high detail inset.

The amount of display area degraded was varied at five levels: none of display area (undegraded), 75% of display area (half of the display's height and width), 91% (70% of height and width), 97.75% (85% of height and width), and 100% (evenly degraded) (see figure 3). The size of the image generated for texturing into the high detail inset was adjusted to ensure constant pixel size corresponding to the fine level of resolution.

Several other variables were controlled. Maximum frame rate was 12, and frame rates did not fall below 11.9. Object location was controlled through the use of four contiguous regions located around the subject (see figure 4). These regions were of equal area, and no regions were located above, below, in front or to the left of the subject when in home position. The horizontal angular extent of each region equaled the Flight Helmet's horizontal field of view, and each region fit entirely into a single view. Care was taken so that objects would not overlap into neighboring regions. Distribution (grouping) of the objects over these regions was varied by sometimes locating all objects within a single region, and at other times distributing the objects over the regions as evenly as possible. Target objects appeared an equal number of times in each region. Objects were randomly located within regions.

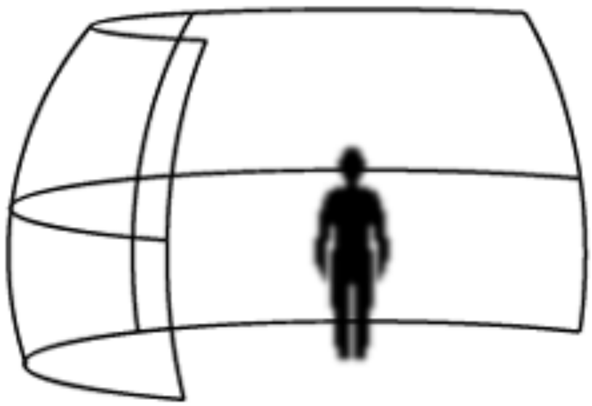

Figure 4: The four regions used to control object location.

Subjects performed a total of 768 correct trials over all but the evenly degraded - coarse resolution display. With the latter display, only 16 trials (with no control of correctness) were performed, to confirm that subjects were not performing at better than chance levels. With the other eight displays, trials were divided equally into two sets. In each set, subjects performed 48 correct trials with one display before moving on to the next. The order in which different displays were presented in a set was randomly varied between subjects, and counterbalanced so that no display was presented as the *n*th display three times, and so that no two display sequences were presented four times.

The experiment was run across two or three days. At the beginning of the first experimental session, subjects were told the nature of the experiment. Subjects were randomly assigned to a button condition and then, at the beginning of the first and every following session, given five trials (one object located directly in front of them, seen at fine resolution) to become accustomed to the button assignment. During the first session, the subject was next given 20 practice search trials to ensure that they understood the general nature of the task. At the beginning of each 48 trial display block, subjects performed five practice trials with the display. None of these practice trials were included in the analyses. The remaining 48 trials in each block represented 2 trials for each of the 4 locations by 2 grouping by 3 number of objects conditions. The order of specific trials was randomized for each subject within each block. For any trial on which the subject made an error, that trial was repeated by placing it back into the queue of remaining trials. The subject with the best combined accuracy and speed of performance was rewarded with $50.

Results

The data from the visual search task were analyzed by means of four factor analyses of variance. We report all significant effects that have a probability level of 0.05 or less. Pair-wise comparisons were used to follow up significant main effects. The independent variables were display, grouping, number of objects, and target location. The dependent variables were mean search time when the target was present, mean search time when target was absent, accuracy when target was present, and accuracy when the target was absent. For all dependent variables, the means are based on collapsing across trials and button assignment. The means for these four measures by display are presented in Table 1. Initially we looked at accuracy of search performance with the evenly degraded - coarse resolution display. Since accuracy in this condition was no different from chance, data from this condition were not included in any further analyses.

The 8 X 2 X 3 X 4 analysis of variance on search time when the target was present revealed four significant main effects and five significant interactions. One of these main effects was caused by display. Follow-up analyses showed that the undegraded, 75% degraded - medium resolution, and 91% degraded - medium resolution displays all had significantly faster search times than the 91% degraded - coarse resolution and the 97.75% degraded - coarse resolution displays. In addition, the evenly degraded - medium resolution, 91% degraded - coarse resolution, and the 97.75% degraded - medium resolution displays had significantly faster search times than the 97.75% degraded - coarse resolution display. No other pair-wise differences were significant.

There were also significant main effects of grouping, number of objects, and location. Search times were faster when objects were grouped (mean = 3.422) than when they were ungrouped (mean = 3.741). Search times were faster when there was one object (mean = 3.183), than when there were three objects (mean = 3.610), which were in turn faster than when there were five objects (mean = 3.952). Finally, search time was faster when the target was in one of the quadrants closest to the home position location than when the target was in the two far quadrants.

Table 1: Average search times and accuracies for the 9 displays examined in the first experiment.

Display Resolution	% Display Degraded	Total Pixels in Display	Search Time Target Present	Search Time Target Absent	% Trials Correct Target Present	% Trials Correct Target Absent
Fine	0	76800	3.168	4.932	96.2	96.3
Medium	100	27648	3.564	5.671	96.4	97.0
Fine/Medium	75	45216	3.267	5.151	96.9	97.8
Fine/Coarse	75	29952	3.586	5.776	97.5	98.0
Fine/Medium	91	35252	3.340	5.092	96.6	97.6
Fine/Coarse	91	15084	3.787	5.850	97.5	96.9
Fine/Medium	97.75	11898	3.551	5.431	98.2	97.2
Fine/Coarse	97.75	7334	4.388	6.867	97.0	97.4
Coarse	100	3072	5.429	5.909	50.6	54.2

Of the significant interactions only one involved display. This was an interaction of display and number of objects. While search time increased with number of objects for all displays, the relative increase was much greater for the 97.75% degraded - coarse resolution display.

The 8 X 2 X 3 X 4 analysis of variance on accuracy when the target was present revealed only a significant main effect of number of objects and a significant interaction of location and grouping. Analysis of the main effect of number of objects showed that accuracy was higher when there was a single object (mean = 98.4%) than when there were five objects (mean = 95.4%), with the three object condition falling in between these two (mean = 97.3%). Examination of the location and grouping interaction revealed that when objects were grouped, accuracy was lowest when the target was located in the upper far quadrant. When objects were not grouped, accuracy was lowest when the target was in the closest, lower quadrant.

The 8 X 2 X 3 X 4 analysis of variance on search time when the target was absent revealed three significant main effects and three significant interactions. Display again had a main effect. Follow-up tests showed that the undegraded display had significantly shorter search times than the evenly degraded - medium resolution and all three peripherally degraded - coarse resolution displays. The 75% degraded - medium resolution display had shorter search times than the 91% degraded - coarse resolution and 97.75% degraded - coarse resolution displays. Finally, all displays had shorter search times than the 97.75% degraded - coarse resolution display. There were also significant main effects of number of objects and grouping. Search times were shorter when there was one object (mean = 5.131) than when there were three objects (mean = 5.918). Search times for five objects fell in between these two (mean = 5.74). Search times were shorter when objects were grouped (mean = 5.146) than when objects were ungrouped (mean = 6.046).

Display and number of objects interacted significantly. For the 97.75% degraded - coarse resolution display, search times increased with number of objects. For all other displays, search times increased between one object and three objects, but search times for five objects fell between those for one and three objects and did not differ from either. There was also a significant interaction of number of objects and grouping. Search times were faster when objects were grouped and there were three or five objects. Grouping could not take place when there was only one object and this caused the interaction. Finally, there was a significant interaction of location, number of objects and grouping. The source of this interaction was the shorter search times for five objects grouped when they were located in the upper, near quadrant.

The 8 X 2 X 3 X 4 analysis of variance on accuracy when the target was absent revealed two significant main effects and one significant interaction. Examination of the main effect of number of objects showed that accuracy was higher when there was one object (mean = 99.1%) or three objects (mean = 97.7%) than when there were five objects (mean = 95.5%). Varying grouping also resulted in a main effect. Accuracy was higher when objects were grouped (mean = 99.2%) than when objects were ungrouped (mean = 95.7%). The single significant interaction was between number of objects and grouping. Again, there was higher accuracy for grouped objects when there was more than one object.

Discussion

This overall pattern of results allows us to draw several conclusions. First, search task performance was affected as expected by number and grouping of objects, and the use of target absent trials. Thus any effects of display that we have found apply across a wide range of visual search difficulty. Second, display did not affect accuracy. Except for the evenly degraded - coarse resolution condition, accuracy was not affected by display. Subjects could perform the search task with an equal level of accuracy with

Table 2: Average search times and accuracies for the five displays of the second experiment.

Display Color	% Display Degraded	Total Bytes of Color in Display	Search Time Target Present	Search Time Target Absent	% Trials Correct Target Present	% Trials Correct Target Absent
Color	0	230400	2.141	2.714	95.15	93.1
Gray	100	76800	4.941	6.793	76.8	72.9
Color/Gray	75	131040	2.528	4.533	95.8	97.0
Color/Gray	91	100164	2.934	5.217	96.7	95.6
Color/Gray	97.75	88068	3.115	5.633	95.4	94.4

any of the other eight displays. The question then is, what effect did the displays have on speed of visual search?

Overall, the undegraded display always yielded the lowest mean search times. However, there were never any significant differences between this display and the 75% degraded - and 91% degraded - medium resolution displays. In turn, these latter two displays yielded faster search times the 75% degraded - and 91% degraded - coarse resolution displays. In general, the use of coarse resolution in the periphery had more of a negative effect on search times than did the area of degradation.

Taken together, these results suggest that one can reduce the LOD in the periphery of an HMD without major reduction in visual search performance (if any). The results also suggest that the area of high detail required to keep performance up is quite small.

EXPERIMENT 2

In this experiment we decreased level of detail by using only gray scale values in the periphery of the display. As in the first experiment, we compared visual search task performance with an undegraded display, an evenly degraded display, and peripherally degraded displays. The key differences were in the type of peripheral degradation and the discrimination component of the task. In this experiment, subjects searched for a target which differed in color only.

Experimental Methodology

The subjects in the experiment were 10 graduate students. All the subjects had 20/40 vision, uncorrected or corrected with contact lens.

This study utilized a six factor, mixed design, very similar to the design of the first experiment. The primary independent variables were again all within-subjects variables. These variables were display (varying in color content and degraded display area, see Table 2), number of objects, and grouping. The three control variables were trial condition, number of trials, and button assignment.

The apparatus used in this experiment was the same as that in Experiment 1 except for two changes. First, while this experiment's objects had the same relative size as the first experiment's, they were not textured with an image of a face. Instead the objects varied only in color. Subjects were asked to find an orange target box in a field of blue distractor boxes. In gray scale display regions, this translated into finding a more luminant target in a field of less luminant objects. Also, in this experiment a different head mounted display was used. Subjects wore a Virtual Research VR 4 HMD. The VR 4 mounts two color LCD displays on the user's head, each with vertical field of view of 36 degrees, and a horizontal FOV of 48 degrees. These two FOVs overlap fully. Each LCD contains an array of 247 x 230 color triads, with a resolution of 11.66 arcmin at the center of the field of view. We used the VR 4 in a monoscopic mode by sending the same image to each of the video inputs. Absolute region and object size was smaller than in the first experiment, but unchanged relative to HMD field of view. The fine level of resolution from the first experiment was used for every one of this experiment's displays.

Subjects performed a total of 480 correct trials, divided equally into two sets, counterbalanced and randomized as before. Each set consisted of five blocks of 48 trials. Subjects either completed both sets in one day, with a break between the sets, or one set per day, over two days.

Results

The data from the visual search task were analyzed by means of four three factor analyses of variance. Pair-wise comparisons were used to follow-up significant main effects. Significant effects are reported when the probability level was 0.05 or less. The independent variables were display, number of objects, and grouping. The dependent variables were mean search time when the target was present, mean search time when target was absent, accuracy when target was present, and accuracy when the target was absent. For all dependent variables, the means are based on collapsing across trials and button assignment. The means for these four measures are presented by display in Table 2.

The 5 X 3 X 2 analysis of variance on search time when the target was present revealed two significant main effects and two significant interactions. Display had a significant effect. The gray scale display yielded longer search times than the other four displays. In addition, the full color display had faster search times than the 97.75% degraded display. No other displays differed significantly. Grouping also had a significant effect. Search times were faster when the objects were grouped in a single quadrant (mean = 3.011) than when they were placed in different quadrants (mean = 3.253).

One of the significant interactions was between grouping and number of objects. Follow-up testing showed that when the objects were ungrouped, search time increased with the number of objects. When the objects were grouped, search time decreased when the number of objects increased. There was also a significant three-way interaction. Analysis suggests that the above two-way interaction is due to the three peripherally degraded displays. In the other two displays this relationship does not hold.

The 5 X 3 X 2 analysis of variance on accuracy when the target was present yielded two significant main effects and one significant interaction. Display again had a significant effect. Subjects had lower accuracies in the gray scale display than in the other four displays. These other four displays did not differ in accuracy. Analysis of the significant effect of grouping revealed that the accuracy was higher when objects were grouped (mean = 93.6%) than when not grouped (90.3%). Grouping also interacted significantly with number of objects. In the ungrouped conditions, accuracy was highest in the single target condition, while when objects were grouped, accuracy was highest when there were three objects.

The 5 X 3 X 2 analysis of variance on search time when the target was absent yielded three significant main effects and four significant interactions. Examination of the significant effect of display showed that search time was longer in the gray scale display than all other displays. The full color display had faster search times than the 91% and 97.75% degraded displays. The full color and the 75% degraded displays did not differ in mean search time, while search times with the 75% degraded display were faster than the search times with the 97.75% degraded display.

Number of objects also had a significant effect. Follow-up analysis revealed that search times were less when there were three objects than when there was one or five objects. Examination of the final significant effect of grouping showed that search times were less when the objects were grouped (mean = 4.754) than when ungrouped (mean = 5.602). Display and number of objects interacted significantly. While the relative ordering of search times for the five displays was the same across one, three and five objects, the absolute difference in search times between the displays increased with the number of objects. Display also interacted with grouping. Again, while the ranking of the displays did not differ for grouped and ungrouped conditions, the relative differences in search time between displays were larger when objects were ungrouped.

Analysis of the significant interaction between number of objects and grouping revealed that in the ungrouped condition, search times increased with the number of objects. In the grouped condition, search times were less when there were three objects. There was also a significant three-way interaction. The locus of this interaction seemed to reside in the differential effects that number of objects and grouping had with the gray scale and 97.75% degraded displays. When objects were ungrouped, increasing the number of objects increased search times for these two displays. For the full color and 75% degraded displays, increasing the number of objects had a negligible effect on search times.

The 5 X 3 X 2 analysis of variance on accuracy when the target was absent revealed three significant main effects and two significant interactions. Display once again had a significant effect. Accuracy with the gray scale display was lower than with the other four displays. No other displays differed in accuracy. Number of objects also had a significant effect. Accuracy was lower when there were five objects (mean = 84.7%) than when there was only one object (mean = 95.3%). When there were three objects accuracy was in between these two conditions (mean = 91.8%). Analysis of the final main effect of grouping revealed that accuracy was lower when objects were ungrouped (mean = 88.8%) than when objects were grouped (mean = 92.4%). There was a significant interaction of display by number of objects. With the gray scale display, increasing the number of objects from one to three significantly lowered accuracy. For the other four displays there was no such effect. Finally, there was a significant interaction of number of objects and grouping. Because grouping cannot occur with a single object, there was no effect in the single object condition.

Discussion

Overall, the pattern of this experiment's strongly suggest that search performance is not greatly affected by the use of peripheral degradation as compared to full color. Accuracy was lower with the greyscale display than with all other displays. No other display differed in accuracy. As to search time, again, the worst performance was with the gray scale display, but performance did decline with increased peripheral degradation. For the target absent trials, search time for the full color display was faster than for the 91% and 97.75% degraded displays. For the target present trials, search time for the full color display was only faster than for the 97.75% degraded display. However, in no case was there a significant difference in performance between the full color display and the 75% degraded display. This pattern of results strongly suggests that elimination of color in the periphery (as defined by the outward 75% of the display area) can be done without greatly affecting search performance.

CONCLUSIONS

The results of both experiments clearly show that we can reduce visual complexity in the periphery without adversely affecting visual search task performance. We would argue that these results provide a strong test of the effects of LOD management by reducing peripheral complexity on visual search performance as in both experiments we reduced detail that was critical to visual search performance. Yet both experiments showed that visual complexity could be reduced by almost half (as measured by number of pixels and bytes of color) without lowering accuracy or speed of visual search.

This is not to say that peripheral information is not needed for performance of our tasks. In the experiments there was a point at which reducing peripheral information hurt performance. For example, the LOD used in the degraded periphery seemed to impact user performance more quickly than the size of the degraded periphery. There also may be tasks where peripheral information is more important than in the task we used. Even so, these experiments strongly suggest that a useful LOD management system might be implemented using a peripheral degradation approach.

Peripheral level of detail degradation should prove to be an effective way of raising frame rates and reducing latencies. Systems that use this management technique will be able to reduce computation with minimal impact on usability. While we have only investigated the use of reduced spatial and color resolution with this management technique, other LOD generation techniques, such as model or simulation simplification, should also be effective. Our results indicate that very significant computational savings might be achieved without eye tracking, although such technology may be required on systems with very small high detail insets.

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